Human-induced climate change: present scientific knowledge and uncertainties

This chapter summarizes what we know about climate change, and where the key uncertainties and gaps in our present knowledge lie. Contrary to the impression you might get from following the debate in the news, we actually know a great deal about the climate — about its present status, observed variation and trends, the extent of human influence on it, and potential future changes. We parse the questions of the reality and importance of climate change into four separate, specific questions.

* *Is the climate changing?*

* *Are human activities responsible for the observed changes?*

* *What are the likely climate changes over the next century or so?*

* *What will the impacts of future climate changes be?*

For each of these, we will review the available evidence and summarize the present scientific consensus, the degree of uncertainty, and the key remaining disagreements.

4.1 Is the climate changing?

Before answering this, we must first define what we mean by "climate." Climate is not just temperature, but also includes such factors as humidity, precipitation, cloudiness, and winds, etc. And it includes not just averages of these factors, but also the variations about the average. For example, some of the most important climate impacts are associated not with increases in mean summer temperature, but increased occurrences of anomalous heat waves.

Although changes in any of these climatic factors can matter, we focus here on temperature because it is the climatic characteristic for which the best data are available and the one that is most directly influenced by greenhouse-gas emissions.

In addition, we must specify where we will look for climate change. We will look for changes in the average surface temperature of the Earth, averaged over the entire year. We do this not because the global average temperature is meaningful to anyone in particular but for practical reasons. No one lives in the global average, and people are far more interested in the particular temperature changes around where they live. However, the global average temperature trend is the most reliable, because smaller-scale regional variations tend to average out, and it is the quantity where we expect to be able to most reliably pick out any warming trend. And temperature is the aspect of climate that we have the best data for and which has the strongest theoretical connection to emissions of greenhouse gases. While we will not discuss it here, we note that evidence exists that other aspects of our climate, such as precipitation, are also changing.

To determine if the Earth's surface is warming, we need measurements of temperature or some related quantity over a long enough period to establish a trend. There are many different sources of relevant data to draw on. None of these is perfect. Each has distinct strengths and weaknesses, and some are more reliable than others overall. We will review several of the most important of these data sources, and show that they paint a consistent picture of rising temperatures. Considered together, these sources provide decisive evidence that the Earth's surface has been warming for the last few hundred years, with particularly rapid warming over the last few decades of the twentieth century.

4.1.1 The surface thermometer record

The simplest way to measure the temperature of the Earth is to place thermometers — such as simple liquid-in-glass thermometers like the one you may have on your back porch — in many locations around the world, and record the temperature at each location every day. By combining measurements taken at locations all over the globe, you can construct an estimate of the average surface temperature of the Earth. People have been making these measurements at thousands of points over the globe, both on land and from ships at sea, for about 150 years. This combined record shows that from 1906 to 2005, the global-average surface temperature of the Earth increased by 0.74°C (Figure 4.1). Most of this increase occurred in two distinct periods, from 1910 to 1945 and from 1976 to the present, with a small cooling between these periods and with many short-term bumps and wiggles throughout the century. (We will discuss the origin of the cooling period, and of the bumps and wiggles, in Section 4.2.) The 1990s were the warmest decade since measurements began in the mid-nineteenth century, and eleven of the last twelve years (1995 -2006) rank among the 12 warmest years in the instrumental record since 1850.

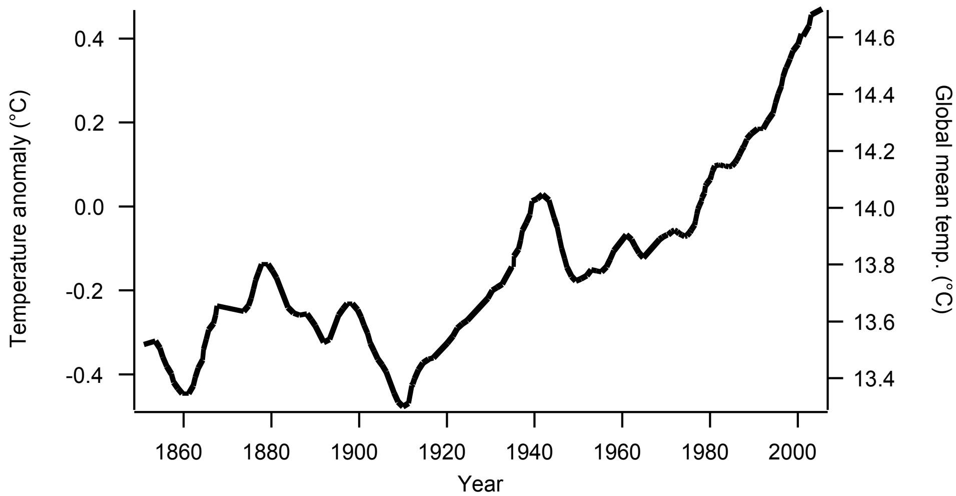


Figure 4.1. Global and annual average surface temperature anomalies (°C), measured relative to the 1961-1990 average. Data have been smoothed to show decadal variations. Source: Figure SPM-3 of the Summary for Policymakers, IPCC (2007).

Note that Figure 4.1 plots 'temperature anomaly' rather than the actual temperature. The temperature anomaly is the difference between the actual temperature each year and some reference temperature. In this figure, the reference temperature is the Earth's average surface temperature between 1961 and 1990, about 14°C. The figure tells us that temperatures between 1860 and 1920 were 0.2-0.4 .C below the 1960-1990 average, while temperatures over the past 10-20 years have been 0.5°C above this average.

Why show 'anomalies,' rather than the actual temperature measurements? The main reason is that many sources of temperature data, such as the glacier data described in the next section, can only measure changes in temperature over time - equivalent to temperature anomalies - not absolute temperature. Because of this, global temperature data are almost always expressed as anomalies, even if they could be expressed as absolute temperatures, so that the records from all data sources can be compared.

The surface thermometer record provides the strongest evidence that the Earth is warming, as well as the most accurate estimate of how much it has warmed. Why is this data set so good? The primary reason is that these data are the most direct measurements of the Earth's temperature. Other methods of determining the trend in surface temperature are *indirect*. They do not measure surface temperature itself, but infer it from some other quantity such as the size of glaciers or the extent of sea ice. For these indirect data sets, converting changes in the observed quantity to a surface temperature trend introduces additional uncertainty. Contrast that to the technology behind the thermometer, which is hundreds of years old. Such technical maturity adds great confidence that the temperature trend observed in the data really represents a warming, not some undiscovered artifact of the instrument being used. Because of these advantages, this data set is the most studied and most trusted in climate-change science.

Despite its strengths, this data set still has imperfections. The 150-year history of continuous observations is in some respects a strength, but changes in how observations were made over that long period can also introduce errors. To illustrate the kind of errors that can occur, consider a hypothetical temperature station that has operated from 1861 to the present. In 1861, it was operated by a farmer, who read a liquid-in-glass thermometer and recorded the temperature every day at noon. While the technology of the thermometer was mature even then, there were occasional errors in the record, because of instrument problems (for example, a bubble in the thermometer), or because the farmer mis-read the thermometer or wrote the temperature down incorrectly. Simple errors like these turn out to be relatively unimportant for discerning a long-term trend, because they are no more likely to go in one direction than the other. As a result, they average out in the long term.

When the farmer died in 1890 his son continued the daily temperature readings, but he made them at 3:00 in the afternoon instead of at noon. Since it is usually warmer in mid-afternoon, the temperatures recorded at this station suddenly jumped upward. In 1902, the barn next to the thermometer burned down and the thermometer was moved to a south-facing hillside that received more sunlight, and the recorded temperatures increased once again. Over the next 50 years, the nearby city grew until it eventually surrounded the farm. Cities are warmer than the surrounding countryside, because roads and buildings are darker than vegetation and so absorb more sunlight — a phenomenon known as the 'urban heat island effect' — so this urban sprawl caused an additional warming trend in the record. These errors, unlike simple reading and recording errors, can introduce spurious trends in the temperature record.

These types of error are well known, and various techniques are used to identify and correct them. For example, changes in observing practices (for example, changing the measurement time from noon to 3 p.m., or moving the thermometer) can be identified by looking for sudden jumps in a station's temperature, then checking the station's log books to see what changed on that day. Once the cause is identified, the station's prior records can be adjusted to account for the change in observing practices. The size of the urban heat island effect can be estimated by comparing a station in a growing urban area with a nearby rural station. While the urban heat island effect can be important in estimating local or regional trends, it is not a major factor in the global trend shown in Figure 4.1: the trend calculated using only rural stations is very similar to that calculated using all observing stations.

The final problem with the surface thermometer temperature record concerns how thoroughly and uniformly the observing stations cover the Earth's surface. The coverage is extensive, but far from complete. Most stations are located where people live or travel, so most measurements are made on land, in densely populated regions. Coverage is thin over the polar regions, uninhabited deserts, and ocean regions far from major shipping lanes. In addition, coverage has changed over time, especially on the ocean. If the newly added regions are on average warmer or cooler than the regions previously observed, this could also create a spurious trend. As with changes in observing practices, scientists are aware of these problems and have developed techniques to determine a robust average temperature from sparse data and to estimate how much bias might still remain in the record. For example, global satellite measurements of seasurface temperature now make it possible to determine accurately what kind of errors in calculating global-average temperature were caused by the earlier sparse coverage of measurements over the oceans, as well as changes in the oceanic coverage.

The surface thermometer record is the most important historical data set used in studies of climate change. The data set has been extensively studied and the potential errors in it are generally well known and well understood. The reliability of the calculated global average temperature is reflected by the size of the so-called "error bars," which give an estimate of the reliability of the calculation. For the warming from 1906 to 2005, the warming is 0.74°C, with an uncertainty of 0.18°C.

But as Chapter 2 stressed, important scientific claims (for example, that the Earth is warming) must be verified by several independent observations before they are widely accepted. In the rest of this section, we discuss other data sets that provide independent estimates of temperature trends.

4.1.2 The glacier record

In cold regions, such as near the poles or at high elevations in mountains, snow that falls during the winter does not all melt during the following summer. Under the right conditions, the snow can accumulate to great thickness over many years, compressing under its own weight to form a thickened sheet of ice known as a glacier. Glaciers presently cover about 10 percent of the Earth's total land area, mostly in Antarctica and Greenland. If the climate warms, glaciers will melt and consequently get smaller or 'retreat.'

Glacier lengths have been measured for hundreds of years, and analyses of historical records show a clear pattern of receding glaciers. Of the 36 individual glaciers monitored over the period 1860-1900, only one advanced and 35 retreated. Of the 144 monitored over the period 1900-1980, two advanced and 142 retreated.

Figure 4.2 shows the average change in length of the world's glaciers since 1700, broken down into 5 regions. Mean glacier length began declining around 1800, with the decrease accelerating gradually over the first half of the nineteenth century. The five regions all show a similar decrease, reflecting the fact that glacier retreat on the century time scale is rather uniform over the globe.

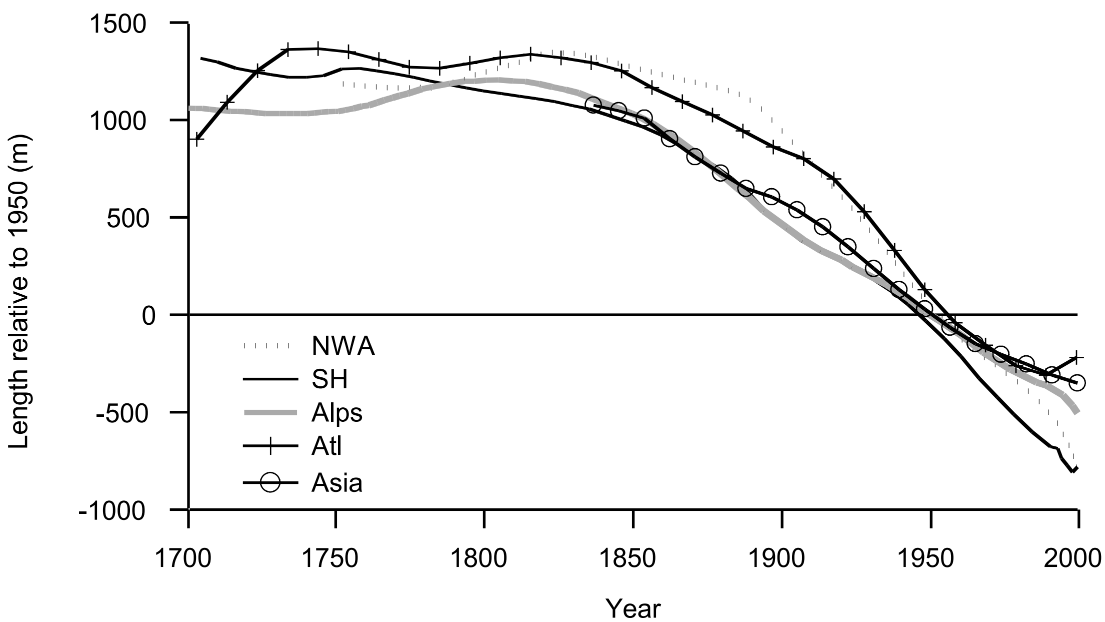


Figure 4.2. Change in mean glacier length as a function of time, broken down into five global regions. SH is the Southern Hemisphere tropics: New Zealand, and Patagonia;

NWA is northwest North America, mainly the Canadian Rockies; Atl is the Atlantic sector, including South Greenland, Iceland, Jan Mayen, Svalbard, and Scandinavia; Alps represents the European Alps; and Asia represents Asian glaciers of the Caucasus and central Asia. After Fig. 4.13 of IPCC [2007]

The most obvious explanation for this widespread retreat of glaciers is a warming climate. Using a simple model of glacier melting, one can infer a warming from the glacier data that is consistent with the warming in the surface thermometer record, providing an independent verification of the warming seen in those data.

Global warming is not, however, the only possible explanation for the observed reduction in glacier length. A decrease in cloudiness, allowing more sunlight to reach the glaciers' surface, could cause increased melting, leading to a similar decrease. Alternatively, since the expansion or retreat of a glacier is determined by the balance between snow accumulation and melting, a decrease in snowfall could also cause glaciers to retreat, even with no increase in temperature. Models of glacier formation and evolution, called 'mass balance models,' can calculate the changes in glacier length that we would expect from each of these climatic changes. It would take a 30 percent decrease in cloudiness or a 25 percent decrease in annual snowfall to cause the same retreat for a typical mid-latitude glacier as a 1°C warming. Such a large change in cloudiness or snowfall could occur locally or even regionally, but worldwide trends this large over a century are unlikely. For this reason, most glaciologists consider a warming trend to be the dominant cause of the observed worldwide glacier retreat.

One limitation of glacier data is coverage. Glaciers are found only in cold places, so a temperature trend calculated from glacier retreat tells only part of the story of worldwide temperature trends, even though it is consistent with the trend in the surface temperature record. We will see below, however, that other data sets with different regional coverage provide similar evidence of warming trends, giving additional support to the idea that the warming we are experiencing is truly global.

4.1.3 Sea level

As the Earth's climate warms, the sea level rises for two principal reasons. First, like most substances, water expands when it warms, so climate warming increases the volume of the water in the oceans. Second, when warming melts glaciers or other ice on land, the melt water runs into the oceans and further raises their level. The opposite effect occurs during ice ages. At the peak of the last ice age, for example, the immense volume of water stored in continental glaciers lowered sea level 120 m below the present level.

Data from tide gauges show that over the twentieth century, global average sea level rose by about 1.5 mm per year, or 15 cm in total over the century (Figure 4.3). The few tide-gauge records that extend back into the nineteenth century suggest that the sea level rose faster in the twentieth century than in the nineteenth century.

Non-climate processes can also affect sea level, complicating attempts to infer a temperature trend. For example, local sinking of coastal land can make local sea level appear to rise, even if the absolute sea level is constant. Such sinking can arise from slow natural movements of the Earth's crust (for example, due to plate tectonics or glacial rebound), or from human activities such as groundwater extraction. We have good knowledge of where such sinking is happening, however, and so can adjust for this in interpreting local sea-level measurements.

Over the last 40 years, sea level has risen at about 1.8 mm/yr. Thermal expansion accounted for about a quarter of this (0.42 mm/yr). The contribution from melting ice is much more uncertain, and can explain most of the rest of the observed sea level rise. From 1993-2003, sea level rose by 3.1 mm/yr, significantly higher than the average rate for the twentieth century. Thermal expansion accounts for about half of this (1.6 mm/yr), with the melting of land-ice accounting for the rest.

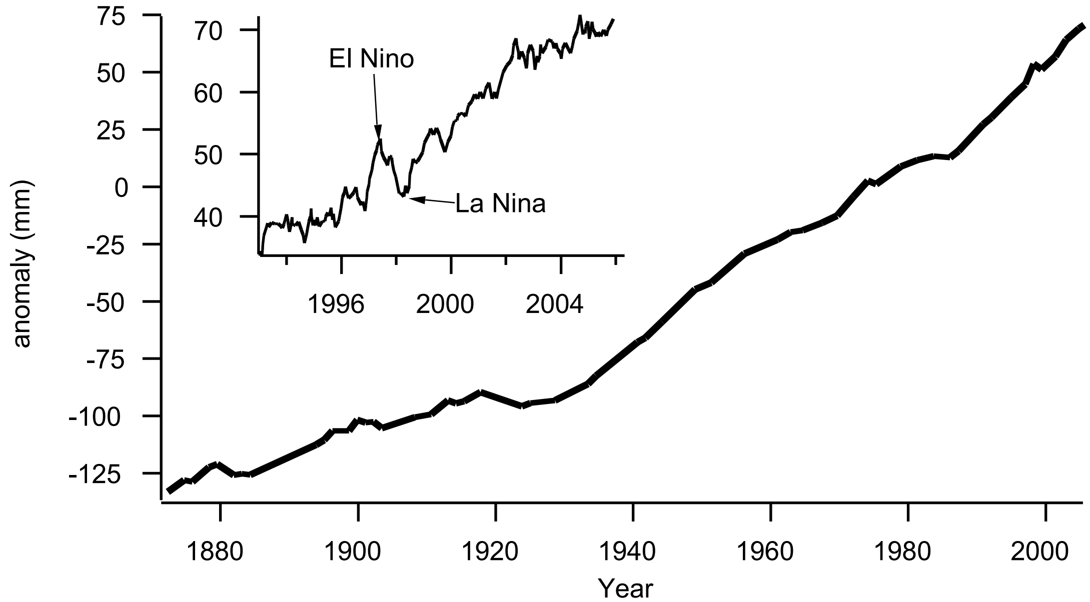


Figure 4.3. Global and annual average sea level anomalies (mm), measured relative to the 1961-1990 average. Data have been smoothed to show decadal variations. The inset plot shows a close-up of unsmoothed 1993 to 2002 anomalies. Adapted from Figures SPM-3 and 5.14 of IPCC (2007).

We note that changes in the amount of water stored on land in forms other than ice, for example in lakes and aquifers, can also change sea level, particularly when ground water is pumped out of aquifers for irrigation or other uses and flows to the ocean. Such changes might be important, but quantitative estimates of their contribution are very uncertain.

4.1.4 Sea ice

Seawater freezes at the cold temperatures found in the polar regions, forming a layer of ice that is typically a few meters thick on the top of the ocean. Given the rapid global warming we are now experiencing, we might expect to see changes in sea ice — and we do.

Figure 4.4 plots the minimum area of Arctic sea-ice each year, which occurs during late summer. There is a clear long-term downward trend: the minimum ice-covered area was about 1.5 million square kilometers smaller in the 2005 than in the late 1970s, corresponding to a rate of loss of 7.4 percent per decade. Losses in summer were greater than losses at other times of the year; averaged over the entire year, the rate of loss of arctic sea-ice area was 2.7 percent per decade.

During the summer of 2007, enough sea ice melted to open up the elusive Northwest Passage. Sought by explorers for centuries, the Northwest Passage is a route from Europe to Asia through the Arctic. Normally impassible except to ice breakers, this route is much shorter than traveling through the Panama Canal (or around the Cape Horn, the southern tip of South America). Given the near certainty of continued Arctic warming over the 21st century, it seems likely that this passageway will continue opening during the summer, eventually becoming an annual event.

In addition to shrinking in area, sea ice has also grown thinner. Measurements from submarines show that, from 1987 to 1997, sea ice thickness in the central Arctic decreased by up to 1 m — a loss of about one-third of the average thickness. Together, these sea-ice measurements provide strong confirmation of the measured warming in the Arctic region.

The decline of sea-ice area does not appear to be occurring in the Antarctic, where sea-ice area has remained stable since the mid-1970s. This is consistent with the fact that temperatures there have not risen significantly over the past few decades.

Finally, we note that these data have clear limits as indications of a global trend. The most obvious is that the sea-ice record indicates warming only in places cold enough for sea ice to form. As such, it provides no information about warming at mid and low latitudes.

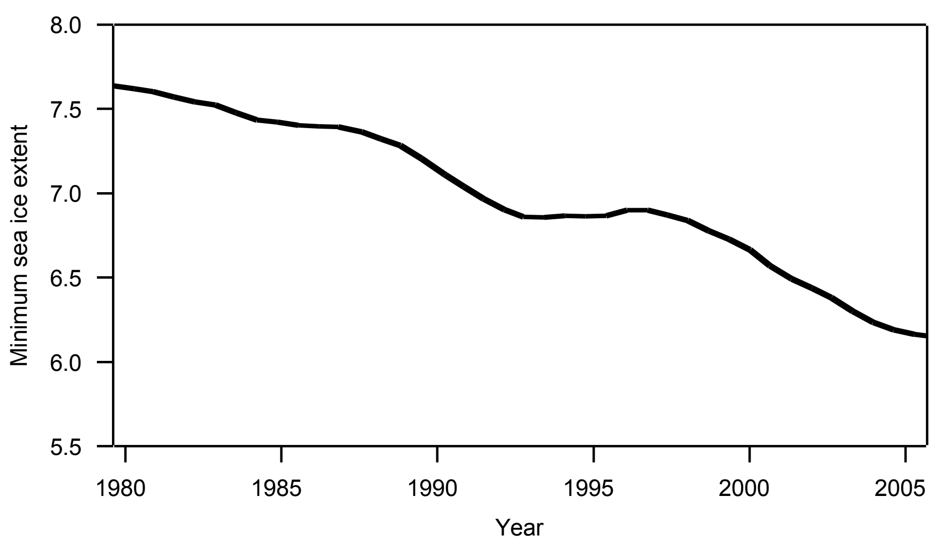


Figure 4.4. Satellite measurements of summertime minimum arctic sea ice extent (in

millions of square kilometers) from 1979 to 2005, smoothed to reveal decadal variations. Source: Fig. 4.9, IPCC (2007).

4.1.5 Ocean heat content

One of the robust predictions of global-warming theory is that some of the energy trapped in the atmosphere by greenhouse gases should end up heating the ocean. To test this prediction, scientists have used millions of ocean temperature measurements to calculate the heat content[1] of the oceans, and this is plotted in Figure 4.5. Taken as a whole, the heat content of the ocean has clearly increased over the past 50 years, although there is significant variability throughout the time series thought to result from changes in ocean circulation.

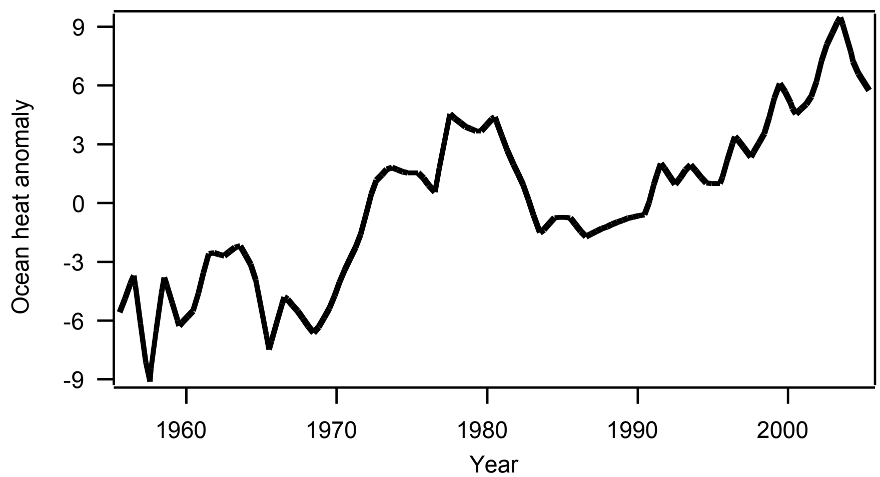


Figure 4.5. Time series of ocean heat content anomaly (in 10^{22} J) for the top 700 m of the ocean (anomalies calculated relative to the 1961-1990 averaged). Adapted from Fig. 5.1, IPCC (2007).

4.1.6 Climate proxies

A ‘proxy’ climate record is a record of past climate variation that has been imprinted on some long-lived physical, chemical, or biological system. Because of their longevity, climate proxies can provide evidence of past climate from long before the modern instrumental record. This section discusses several of the most important and widely used sources of climate proxy data and what they tell us of past climates.

[1] Heat content is equivalent to temperature, so an increase in heat content means that the oceans temperatures are rising.

Tree rings

Tree growth follows an annual cycle, which is imprinted in the rings in their trunks. As trees grow rapidly in the spring, they produce light-colored wood; as their growth slows in the fall, they produce dark wood. Because trees grow more — and produce wider rings — in warm years, the width of each ring gives information about climate conditions around the tree in that year. The rings of a long-lived tree can provide a temperature time series that extends back hundreds of years.

The key to using tree rings as a climate proxy is finding a quantitative relation between tree-ring width and temperature in the tree's location. This is done by examining rings from recent years when thermometer records are also available. Once a relationship between ring width and temperature is estimated for a recent period, this relationship can be used to estimate the temperature for the period before there were direct measurements.

There are two principal difficulties to using tree rings as a climate proxy. First, it is difficult to separate temperature's effects on tree growth from those of other climate characteristics such as rainfall. One way to handle this is to carefully select your trees to be in regions where, over the past century or so, tree growth has been insensitive to precipitation and primarily responsive to temperature. Second, tree-ring temperature reconstructions assume that the relation between tree-ring width and temperature determined from recent data applies over the entire life of the tree. There is no real way to know whether this is so or not. Further, tree-ring reconstructions are available for only a small part of the Earth's surface. They are obviously not available over oceans. Nor are they available from desert or mountainous areas where no trees grow, or from the tropics, because the small seasonal cycle there means that trees grow year-round and so produce no rings.

Ice cores

Both Greenland and Antarctica are almost entirely covered by glaciers, some thousands of meters thick. We discussed above how the advance or retreat of glaciers gives information about temperature changes over the past few centuries, but in addition to this, the chemical and physical characteristics of the glacial ice provide a rich store of information about conditions at the time the snow fell.

The chemical composition of the ice, such as the fraction of heavy isotopes of hydrogen and oxygen (forms of hydrogen or oxygen atoms that contain extra neutrons), can be used to infer the air temperature around the glacier when the snow fell, as can variations in the size and orientation of ice crystals. And small air bubbles trapped when glacial ice is formed preserve a snapshot of the chemical composition of the atmosphere at that moment. In addition, the amount of dust trapped in the ice conveys information about how wet or dry the regional climate was when the ice formed, because more dust blows around during droughts, and about prevailing wind speed and direction. Finally, sulfur is one of the main effluents of volcanoes. Once emitted to the atmosphere, this sulfur dissolves in rain, forming sulfuric acid, which is transferred to the ice when rain or snow falls on the glacier. Measurements of the acidity of glacial ice consequently tell us whether there was a major volcanic eruption around the time the ice was formed.

Researchers retrieve a time series of all this information by drilling down into the ice sheet with a hollow drill bit and removing a long column of ice, a few inches in diameter, known as an ice core. The further down you drill, the older is the ice you retrieve. Reconstructing information about historical climate from an ice core requires two steps. First, the age of each layer of ice must be determined from its depth inside the glacier. Although much effort has been spent on this problem, it still carries important uncertainties, because the rate of ice accumulation varies over time and because ice inside the glacier can compress and flow under the great weight of the ice above. Second, the characteristics actually observed must be translated into the climatic characteristics of interest — for example, translating abundance of heavy isotopes of hydrogen to temperature, and amount of dust to precipitation — introducing additional uncertainties. Ice cores have provided climate reconstructions back an amazing 800,000 years.

Corals

Corals are small marine animals that live in colonies anchored to reefs in warm ocean waters, mostly in tropical latitudes. The reefs, which are made up of skeletons of previous generations of coral, can be thousands of years old. The chemical composition of the reef can provide information about past climate and ocean conditions. Quantities such as ocean temperature, precipitation, salinity, sea level, storm incidence, and volume of nearby freshwater runoff are all obtainable. As with ice cores, these data give a time series of historical conditions over the life of the reef, subject to two important uncertainties: determining the age of each bit of coral, and converting its chemical make-up to quantities of interest, such as the average ocean temperature.

Ocean sediments

Billions of tons of sediment accumulate at the bottom of the ocean every year. Like ice cores and corals, this sediment contains information about nearby climate conditions when it was deposited. The most important source of information in sediments comes from the skeletons of tiny marine organisms. The ratio of the abundance of species that thrive in warm waters to the abundance of species that thrive in cold water tells us about the surface water temperature. The chemical composition of the skeletons and variations in the size and shape of particular species provide additional clues. In the end, information about water temperature, salinity, dissolved oxygen, nearby continental precipitation, the strength and direction of the prevailing winds, and nutrient availability can all be obtained from ocean sediment. Ocean sediments can provide information on the climate back many tens of millions of years.

Boreholes

Temperatures measured today at different depths underground provide a different way to infer how the surface temperature varied in the past. To understand how this works, think about cooking a frozen turkey. You can tell how long the turkey has been in the oven by measuring the temperature at different depths below its skin. If the turkey is hot on the surface but still frozen just below the skin, then it has been cooking for only a short time. If the center of the turkey is 165°F, then it has been in the oven for several hours — and you should take it out before it is overcooked! In an analogous way, measuring the temperature of the Earth at many depths in deep narrow holes called boreholes allows you to infer the history of the ground surface temperature over the past few hundred years.

One issue is that the borehole measurements tell us about the temperature of the ground. The surface thermometer measurements, on the other hand, tell us about the temperature of the air a few meters above the ground. Usually the difference in trends derived from these two sources is small, but depending on the properties of the surface — for example, land-use and land cover, soil moisture, and winter snow cover — significant differences can exist. In central England, for example, where the ground is rarely snow-covered and major land-use changes have not occurred for several centuries, surface temperature trends inferred from borehole records are very similar to those in thermometer records. But in northwestern North America, borehole estimates of surface warming in the twentieth century are 1-2°C larger than the warming in the thermometer record, most likely because of changes in average snow-cover and land-use during the century. Such discrepancies are considered and controlled to the extent possible in order to construct a consistent historical temperature record.

What proxy data tells us about past climates

Each of the proxies discussed, and several that we did not, provides a different view of climate history: for example, ice cores provide information about polar regions back a few hundred thousand years, while tree rings provide information about midlatitude climate back a few hundred years, and corals provide information about the tropical sea temperatures back a few thousand years. While each individual data source has unique coverage in time and space, and its own uncertainties, taken together it is possible to construct a reasonably complete picture of the climate back 100 million years — and in some cases, well beyond.

We clearly see in the proxy data that climate is not now nor has it ever been fixed. Rather, it has displayed important and surprisingly large variations throughout the Earth's entire history. For example, about 700 million years ago, evidence suggests that snow and ice covered the entire planet, leading to what scientists refer to as "snowball" Earth.

Figure 4.6 shows a measure of the Earth's temperature over the last 70 million years. Peak temperature occurred about fifty million years ago, during a period known as the Eocene climatic optimum. During that time, the planet was far warmer than today. Forests covered the Earth from pole to pole at that time, and plants that are intolerant of even episodic freezing, as well as alligators and other animals currently restricted to the tropics, were found in the Arctic. Then the Earth started cooling. By about 35 million years ago, the polar regions had cooled enough that an ice sheet first appeared on Antarctica. The general, long-term cooling trend has continued, right up to today.

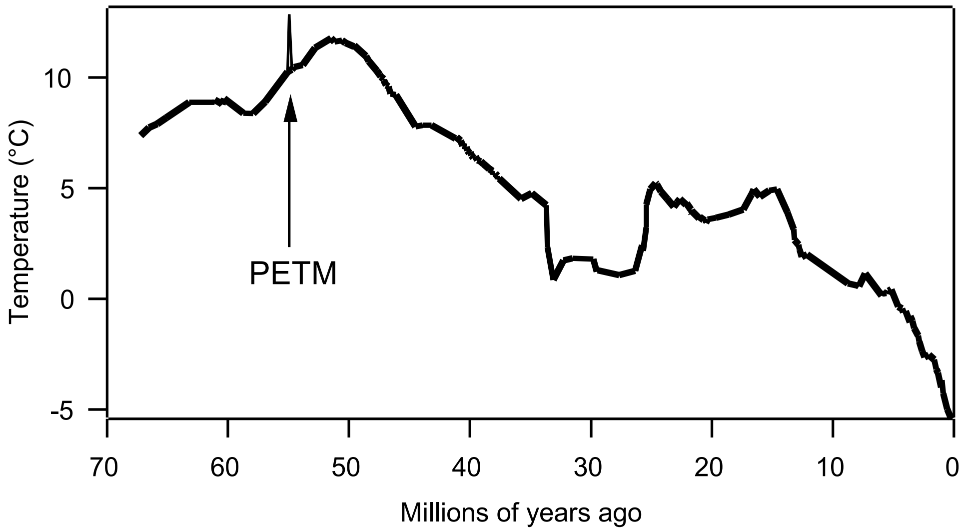


Figure 4.6. A measure of the temperature[2] of the Earth's polar regions over the last 70 million years. The spike in temperatures 55 million years ago is known as the Paleocene-Eocene thermal maximum or PETM. After Fig. 2 of Zachos et al., 2001.

Figure 4.7 shows temperature changes over the past four million years. Consistent with Fig. 4.6, Fig. 4.7 shows a general cooling trend. It also shows that, starting around three million years ago, about the same time that ice sheets, like the one we find on Greenland today, appeared in the Northern Hemisphere, the Earth's temperature began large oscillations between warm and cool periods. During the cool phases, the ice sheets rapidly grew and covered large parts of the Northern Hemisphere — and these periods are therefore known as "ice ages." The warm periods between the ice ages are generally referred to as "interglacials."

From about two and a half million years ago to one million years ago, the ice ages occurred every 41,000 years. Beginning about one million years ago, a transition occurred and the ice ages began repeating about every 100,000 years.

[2] Beginning about 35 million years ago, some of the variations reflect variations in ice volume rather than temperature. The overall trend, however, generally represents temperature.

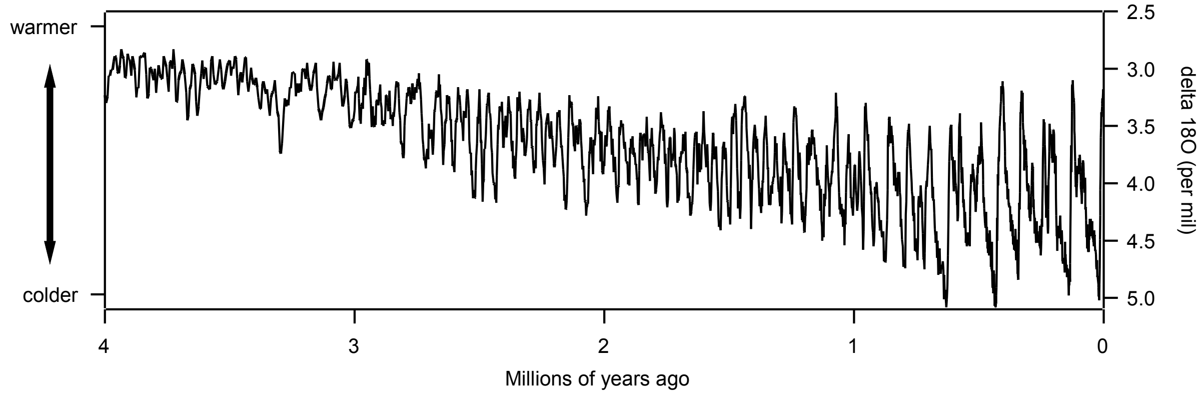
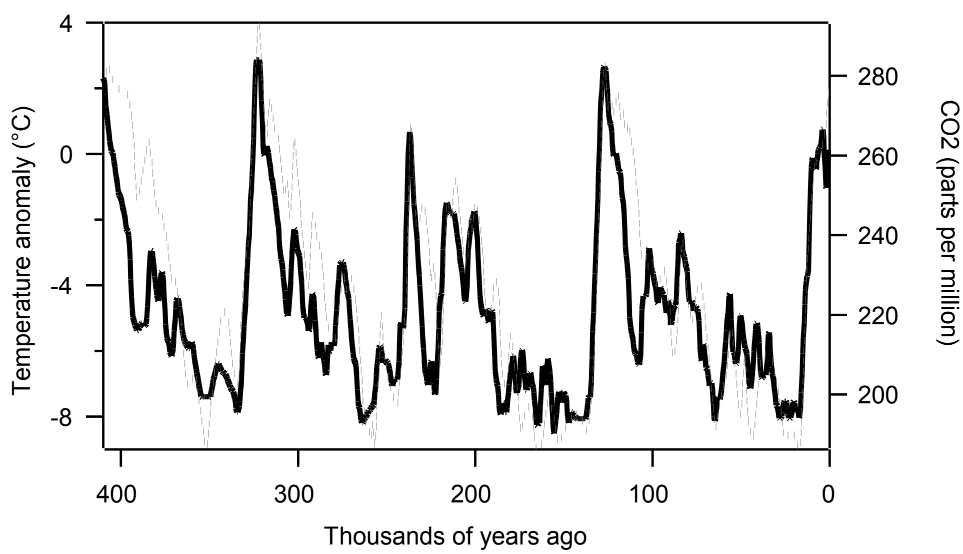


Figure 4.7. Measurement of relative temperature over the last four million years. Based on the data of Lisiecki and Raymo[3]

Figure 4.7b shows data from an ice core in Antarctica — temperature variations calculated from the isotopic composition of the ice and atmospheric CO_2 concentrations obtained from air bubbles trapped in the ice — that go back an astonishing 410 000 years. We see the oscillations in Fig. 4.7 in much greater detail here. In particular, we see relatively short (10,000-30,000 years) and warm interglacials surrounded by comparatively long and cold ice ages (100,000 years). The descent into the ice ages is gradual, taking several tens of thousands of years to cool down, while the warming associated with the end of the ice age occurs rapidly.



[3] The actual measurement is the abundance of oxygen-18. There is, however, no clear consensus on how to convert this isotopic abundance to temperature, although there is agreement that variations are related to temperature variations. Thus, we present here only qualitative temperature changes.

Figure 4.7b. Temperature anomaly (black line), relative to the present-day temperature, inferred from the chemical properties of an ice core from Antarctica, from 410 000 years ago to the present. Carbon dioxide (gray dotted line) is from air bubbles trapped in the ice. Source: adapted from Petit et al. [1999].

Today's interglacial is cooler by about 2-3°C than the previous four interglacials. We also note that the ice ages are generally thought to be 5-8°C colder than today — a small value considering that the Earth was essentially a different planet back then, with glaciers several thousand feet thick covering much of North America and sea level 300 feet lower than today. As we will discuss in Section 4.2, changing CO_2 has played an important role in most of the variations in Figs. 4.6, 4.7, and 4.7b.

Figure 4.8 shows reconstructions of large-scale average temperature anomalies for the last 1100 years based on several different climate proxies. While differences between the various reconstructions exist, they all show a similar pattern. Temperatures were warm about 1000 years ago, during a period known as the medieval warm period. There was then a cooling for several centuries, culminating in a period in the middle of the millennium known as the little ice age. The temperatures bottomed out 200-300 years ago, and since then the temperature of the Earth has been rapidly increasing.

Based on these reconstructions, it can be said with a high level of confidence that the Earth's temperature was higher during the last few decades of the 20^{th} century than during any comparable period during the last 400 years. This conclusion is based on consistent evidence from a wide variety of geographically diverse proxies.

It is far more difficult to say whether temperatures are warmer today than during the medieval warm period. Presently available proxy evidence indicates that temperatures at many, but not all, individual locations are indeed higher today. However, the uncertainties associated with reconstructing hemispheric mean or global mean temperatures back that far are large and therefore prevent a confident conclusion on this point. It is certainly possible, however, that the temperature of the last few decades are higher than any period of comparable length since 900 A.D.

It is also useful to recognize that, overall, our climate is has been relatively stable over the last thousand years. Figs. 4.6 and 4.7b show variations of 10°C in the past — far larger than variations of a few tenths of a degree C over the last thousand. Many anthropologists credit the explosive success of human civilization over the last few hundred years to the relatively warm, relatively stable climate we have experienced.

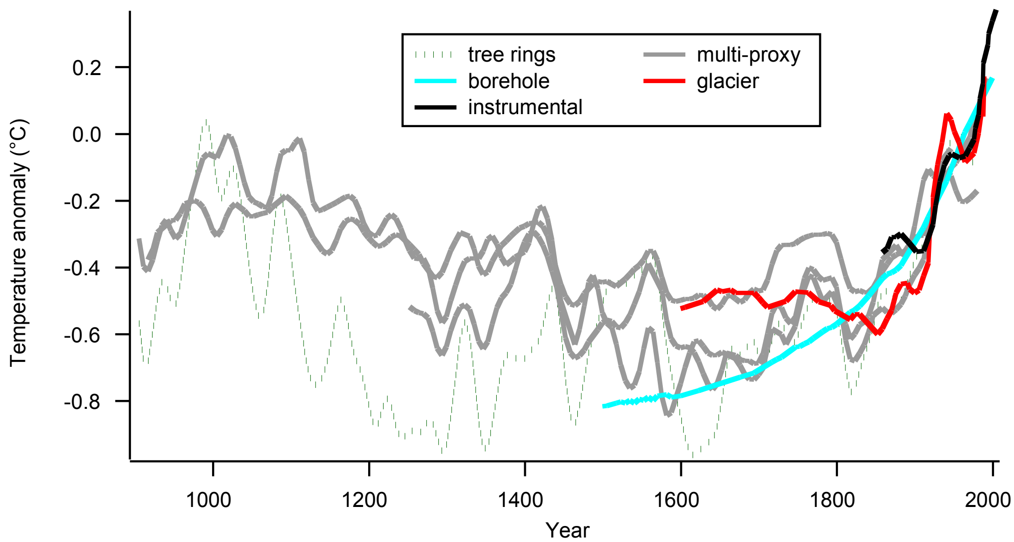


Figure 4.8. Different estimates of large-scale average surface temperature variations from six different research teams and proxy records, as well as the instrumental record of global mean surface temperature (Figure 4.1). Adapted from Figure S-1 of NAS [2006].

4.1.7 Satellite temperature measurements

Meteorological satellites have provided a new, independent source of data about global temperatures since 1979. One type of satellite instrument in particular, the Microwave Sounding Unit (MSU), measures microwave radiation emitted by the Earth's atmosphere, from which it is possible to calculate the temperature of the atmosphere at various altitudes. As a measure of global-average temperature, this satellite data set has the distinct advantage that it covers the entire Earth, including the oceans and uninhabited land areas, and so avoids potential problems from partial or biased coverage.

The MSU data also have some critical weaknesses. First, the observations cover less than three decades, a rather short period from which to draw strong conclusions about trends. Second, the MSU temperature record is stitched together from data from about a dozen satellites, with only one or two satellites operating at any given time. As a result, a problem with any single satellite can adversely impact the entire climate record. In contrast, the surface thermometer record (Section 4.1.1) is produced from hundreds or thousands of individual thermometer measurements every day, providing a beneficial redundancy that makes the record insensitive to malfunction of individual instruments.

Because the satellite record is compiled from data from a number of satellites, intercalibration is a key issue in determining temperature trends. To understand why, suppose you are keeping track of your weight to tell if you are gaining or losing. Further, suppose your scale breaks, and a month passes before you buy a new one. If the new scale says you are 2 pounds heavier than your last reading on the old one, does this mean you have gained 2 pounds? Or does the new scale just weigh everything 2 pounds heavier than the old one? You could avoid this problem by buying a new scale before the old one breaks, and measuring yourself on both scales for a while to estimate the difference between them — if you had the foresight, patience, and money to do this.

The MSU record suffers from the same problem, because each satellite only lasts a few years. The agency that operates them (the US National Oceanographic and Atmospheric Administration, or NOAA, which includes the National Weather Service) tries to launch each new satellite while the previous one is still operating, to provide a long enough period of overlapping measurements for comparison. But since you cannot predict precisely when an instrument is going to fail, NOAA has not been entirely successful in obtaining long enough overlapping records. In particular, the NOAA-9 satellite had only a short overlap with the NOAA-7, -8, and -10 satellites, and the temperature trend estimated from the MSU data is quite sensitive to how you connect data from satellites that flew before NOAA-9 to those that flew after.

A final caveat is that the satellite instruments do not measure the temperature of the Earth's surface, but measure the temperature of the atmosphere averaged over a relatively thick layer. The most commonly quoted measurement is the average temperature of the lower troposphere, a layer of the atmosphere from the surface to an altitude of about 8 km (about the height that commercial aircraft fly). Figure 4.9 shows global-average temperature anomalies of the lower troposphere calculated by two independent scientific groups. Also shown is the lower-troposphere anomaly calculated from measurements made by thermometers carried aloft by weather balloons.

All three data sets show a similar increase in temperature as well as similar year-to-year variations, which are driven mainly by internal variations like El Nino. The University of Alabama in Huntsville (UAH) group estimates a warming trend of 0.12 ± 0.08°C per decade between 1979 and 2004, while the Remote Sensing Services (RSS) group estimates a warming trend of about 0.19 ± 0.08°C per decade. We note that the UAH and RSS groups are analyzing the same raw measurements from the MSU instruments. The differences in the trends they calculate come from different assumptions about how to handle the technical details of the calculation, such as the satellite-to-satellite calibration problem described above. These differences indicate that these data cannot at present provide a precise estimate of warming of the lower atmosphere but only a relatively wide range. Interpreting these data is an active area of current scientific research, and it is likely that future research on this data set will allow this wide range to be substantially reduced.

The trend in the balloon-based measurements from 1979-2004 is 0.14 ± 0.07°C per decade. Balloon-based temperatures are available back to 1958, and the trend from 1958-2004 was 0.16 ± 0.04°C per decade[4].

Thus, the MSU satellite data as well as balloon-based temperature measurements are unanimous in finding a significant warming of the lower atmosphere over the past few decades. The calculated trends in lower-atmospheric temperatures are broadly consistent with the trends in surface temperatures, although some discrepancies still exist. Over the past decade, these discrepancies between the satellite and surface record have been used to attempt to cast doubt on the reality of the observed warming trend. We will discuss this argument in detail in Chapter 7.

[4] This is the trend in the Hadley Centre Atmospheric Temperatures (HadAT2) data. The trend in a similar data set, the Radiosonde Atmospheric Temperature Profiles for Assessing Climate (RATPAC) from NOAA is 0.13 ± 0.03°C per decade.

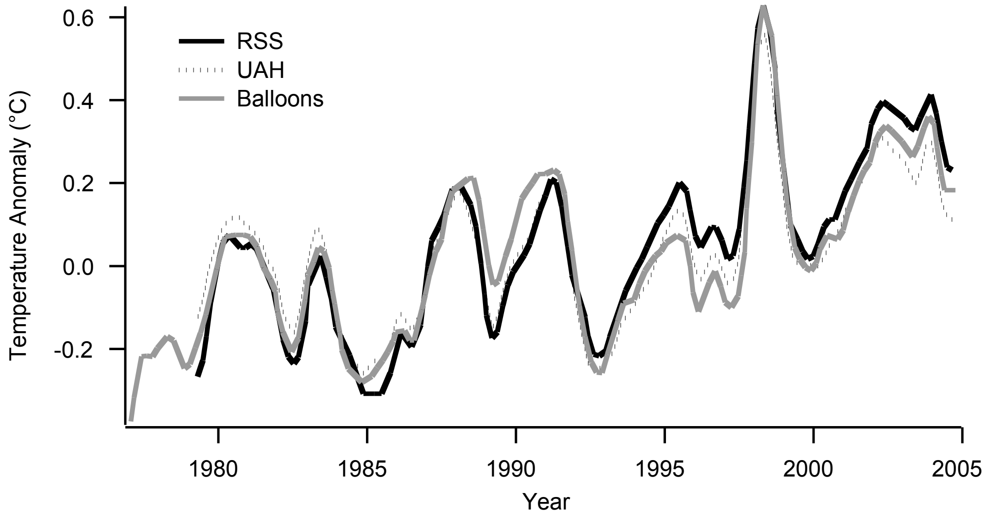


Figure 4.9. Time series of globally averaged lower atmospheric temperature anomalies. The solid line is the calculation by Remote System Services (RSS), the dotted line is the calculation from the University of Alabama at Huntsville (UAH). The gray line is the anomaly time series from balloon-borne thermometer measurements (HadAT2 data). The anomalies are calculated relative to the 1979-1997 average. Source: Fig. 3.3a of the CCSP report (2006).

4.1.8 Summary: is the Earth warming?

Table 4.1 summarizes what we know about trends in the Earth's temperature. All this evidence has been peer reviewed and multiply verified by independent scientific groups. No data set is perfectly reliable, of course. It is still possible that any one of these data sets could be significantly in error, although the critical scrutiny and multiple verifications that each of them has received minimizes this risk. But there is essentially no chance that enough of these data sources could be wrong by far enough, and all in the same direction, that the overall conclusion of substantial global warming in the 20th century could be wrong. Under the weight of this abundant, consistent, thoroughly checked evidence, the IPCC's Fourth Assessment Report concluded that the warming of the climate system is now unequivocal.

Table 3-1. A summary of measurements of changes in the Earth's temperature

Type of Data	**Direction of 20th Century Change**	**Size of Change, Comments**

Surface thermometer measurements	Warming	Average surface air temperature increased about 0.7°C (1.3°F) over the 20th century, with the rate of warming in the last half of the century about twice the rate of the first half.
Glaciers	Warming	Glaciers have been receding worldwide for the last two centuries, with evidence of faster retreat in the 20th century.
Sea level change	Warming	Sea level rose about 17 cm total over the 20th century. Most of this rise came from thermal expansion of ocean water and from melting of land ice. We have high confidence that sea level rose faster in the 20th than in the 19th centuries.
Sea ice	Warming	The area of Arctic sea ice has decreased by 2.7 percent per decade over the past 30 years, with decreases in summertime minimum area of 7.4 percent per decade. Average thickness of Arctic sea ice has also decreased over this time.
Ocean temperature	Warming	The heat content of the top 700 m of the ocean has significantly increased over the past 50 years.
Climate proxies	Warming	The Earth's temperature was higher during the last few decades of the 20th century than during any comparable period during the last 400 years.
Satellite	Warming	Satellite measurements since 1979

temperature measurements		show warming broadly consistent with surface warming.

The data we have presented in Section 4.1 and Table 4.1 is just a subset of the evidence that exists supporting the claim that the Earth is warming. Other evidence of warming includes a decline in Northern Hemisphere snow cover over the last few decades, changes in the Arctic permafrost, and strengthening of mid-latitude westerly winds in both hemispheres since the 1960s. In addition, there have been widespread changes in extreme temperatures over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent. Dates that lakes freeze over has been shifting to later in the year, with some lakes that used to freeze over no longer doing so. Dates that the ice covering lakes melts has been shifting to earlier in the year. The biosphere has also been changing in a manner consistent with warmer temperatures — with plants blooming and insects emerging earlier than in the past.

Some contrary evidence does exist, such as the lack of a decline in Antarctic sea ice. However, such evidence is rare and vastly outnumbered by the evidence that the planet is warming. As a result, the last IPCC report concluded that "Warming of the climate system is unequivocal."

4.1.9 What is NOT evidence that the Earth is warming

The Earth is warming. But not everything we see that is consistent with global warming gives additional support to this conclusion. This may seem paradoxical, but it is not. The distinction between 'being consistent with' warming and — providing additional support for — warming is best illustrated by one-time or regional events such as the disintegration of the Larsen B ice shelf in 2002. An ice shelf is an ice mass floating on the ocean, formed when a glacier flows into the ocean and extends away from the shore like a floating dock. Over a one-month period in early 2002, the northern section of the Larsen B ice shelf — a mass of ice about 250 meters thick covering more than 2500 square kilometers — spectacularly shattered, creating thousands of enormous icebergs.[5] Scientists agree that the breakage was caused by warming in the region around the ice sheet, but what caused this regional warming? We simply do not know. It is

[5] See Revkin, A. C. "Large ice shelf in Antarctica disintegrates at great speed", New York Times (Late edition (East Coast)), March 20, 2002, p. A13.

possible, perhaps even probable, that global warming played a role. But regions of the Earth, even regions as large as the United States, can experience warm or cool periods even in the absence of any global trend. Look around the world at any time, and you will almost always see a heat wave going on somewhere, and a cold spell going on somewhere else. You cannot infer a global trend from such local extremes, because local or regional behavior can be different from the global average. The same is true for short-term events. As we discussed above, many glaciers have had periods of growth lasting a few decades over the past few centuries, within a longer-term, worldwide trend of substantial glacier retreat. If you looked at a single glacier during one of these growth periods, you might conclude that the Earth was cooling, but this would be erroneous.

The point of this distinction is not to read too much into regional events or short-term trends, however dramatic these may be. You can say that discrete events like the Larsen B collapse are 'consistent with' global warming, but such a single event, by itself, adds little to our confidence that the Earth is warming. The conclusion that the Earth is warming sits on the much stronger foundation of many independent pieces of evidence, over the entire world, over many decades or centuries.

4.2 Are human activities responsible for global warming?

The second question concerns the causes of the recent warming documented in Section 4.1: are human activities responsible, or might recent warming be caused by some natural process? This question is harder to answer than the question of whether the Earth is warming, since establishing a cause-and-effect relationship requires an inference that merely identifying a trend does not. Showing human causation requires both demonstrating that human emissions can account for the observed warming trends, and showing that other potential explanations cannot.

While human emissions are an obvious potential cause of twentieth-century warming, it is entirely reasonable to question whether they really are responsible. As discussed in Section 4.1.6, the climate has undergone large fluctuations over virtually the entire period for which we have information about the planet's temperature. Except for the changes of the last century or so, these climate fluctuations took place long before human activities could have played any conceivable role.

In this section we examine available knowledge about the potential causes that have been proposed for the observed warming of the last century, including human emissions and natural processes. We find that, for the last half of the twentieth century at least, human emissions of greenhouse gases very likely account for most of the warming.

4.2.1 Tectonic processes

Tectonic processes refer to those geological processes that control the locations of continents and ocean basins. It turns out that these processes can affect our climate in a number ways. Whether a continent is located in the tropics or at high latitudes determines how much land area is potentially covered by snow and ice, as well as changing the atmospheric wind patterns. The amount of snow affects the reflectivity of the planet while the wind patterns can change heat transport. Thus, a continent moving from low to high latitudes — or vice versa — can change the climate. It is believed that a significant glaciation in the Paleozoic, about 250 million years ago, was initiated by the slow drift of continents.

The locations of surface features, such as mountain ranges, also have a profound influence on our climate. The Northern Hemisphere has several large mountain ranges in mid-latitudes — the Rockies, the Himalaya, and the Alps. The Southern Hemisphere mid-latitudes, on the other hand, contain mostly oceans. Without any land to break them up, winds blow fiercely around the globe at about 50°S latitude. This strong flow shuts off the transport of warm air from lower latitudes, and is an important reason that the Antarctic is colder than the Arctic.

The distribution of continents also determines the distribution of ocean basins. This in turn determines the location and strength of the world's ocean currents. Ocean currents transport enormous amounts of energy out of the tropics, leading to a significant warming of the mid- and high latitudes. For example, the climate of Western Europe is today warmed by the flow of warm water from the tropics in the Atlantic's Gulf Stream. When this current temporarily shut down about 11,000 years ago, the climate of the Northern Hemisphere cooled dramatically. Movement of the continents can alter the shape of the ocean basins, thereby altering the flow of ocean currents — and our climate.

Finally, tectonic activity also can affect the climate by regulating atmospheric CO_2. Atmospheric CO_2 dissolves in rainwater, and once in a raindrop, the CO_2 molecules react with H_2O to form carbonic acid, the same weak acid that is found in carbonated soda. As a result, rainwater is a weak acid. When it falls on rock, it can chemically dissolve the rock, and in the process the CO_2 molecule is transformed in a molecule of calcium carbonate. This process is known as “chemical weathering.” This calcium carbonate molecule is then transported with the run-off into the ocean, where through various biological processes it is eventually buried in ocean sediment.

The power of chemical weathering was illustrated about 40 million years ago, when the Indian subcontinent collided with the Asian continent to form the Himalayas and the adjacent Tibetan Plateau. (Collisions between continents happen slowly: this one is still going on today.) The prevailing winds brought heavy rainfall onto the newly exposed rock of these geological features, and the resultant chemical weathering drew down atmospheric CO_2.

Could any of these tectonic changes be responsible for the warming of the last few decades? The answer is almost certainly no, because tectonic processes are too slow. It takes a tectonic process millions of years to make an impact on our climate, so any change in our climate over a few decades or even a few centuries could not have been due to any tectonic processes.

4.2.2 Orbital variations

It has been known since the Renaissance that the Earth’s orbit is not a perfect, unchanging circle, but an ellipse whose shape and orientation change slowly over time three ways. These orbital variations can be broken down into three types. First, the average distance between the Earth and the Sun slowly increases and decreases, completing a cycle every 100 000 years. Second, the time of year when the Earth is closest to the Sun varies. At present, the Earth is closest to the Sun during Northern Hemisphere winter, but in 10 000 years the closest approach will be in Northern Hemisphere summer. Third, the tilt of the Earth’s polar axis relative to the Sun, which is now about 23°, slowly oscillates between about 22° and 25° over a period of 40 000 years.

The variation in average Earth-Sun distance changes the total amount of solar energy reaching the Earth. Since the climate is driven by solar energy, this variation clearly can change the climate. The other two forms of variation do not change the total sunlight reaching Earth, but change its distribution during the year and over the Earth’s surface. For example, variation in the Earth’s tilt alters how much sunlight falls on the tropics relative to the polar regions. Such changes in the distribution of sunlight can also affect the climate.

It is now widely agreed that these slow orbital variations trigger the cycling between ice ages and warm interglacial periods that the Earth has experienced over the past few million years (see Figures 4.7 and 4.7b) — a conclusion based on the near-perfect agreement between the timing of the orbital variations and of the timing of the transitions into and out of ice ages.

So if orbital changes drive the climate changes of the past few hundred thousand years, could they also be causing the warming of the past century? They almost certainly cannot, because these orbital wobbles are so slow that it takes thousands of years for them to make any significant change in the pattern of incoming sunlight. The warming of the past century has been much too fast to be caused by these slow orbital variations. The warming must be due to other causes.

4.2.3 Volcanoes

Volcanic eruptions can change the climate two ways. First, volcanoes emit CO_2. In fact, on geologic time scales, the abundance of CO_2 in the atmosphere is set by a balance between emissions from volcanoes and slow removal into the ocean by chemical weathering and biological activity. And since CO_2 is a greenhouse gas, volcanic emissions have the potential to warm the climate.

Volcanic eruptions also change the climate by blowing dust, ash, and sulfur gases into the atmosphere. The dust and ash settle out relatively quickly, but the sulfur gases are oxidized and combine with water to form small, suspended droplets known as aerosols. These aerosols block incoming sunlight, cooling the Earth for several years after a major eruption. In 1816, for example, after three major eruptions in three years, the northeastern USA experienced the famous 'year without a summer' (see, for example, Stommel and Stommel, 1983). Snow fell in Vermont in June and summer frosts killed many crops, leading to widespread food shortages. When that summer was followed by a winter so cold that the mercury in thermometers froze (this happens at -40°C), many residents fled the Northeast and moved south.

Could volcanic eruptions somehow account for the observed warming? One way is if volcanic emissions of CO_2 were responsible for the observed buildup of CO_2 in our atmosphere over the last two centuries. As we will show in Section 4.2.6, we can rule that possibility out: virtually all of the increase in CO_2 in the recent past is due to human activities, primarily the burning of fossil fuels.

A second possibility is if today's warming is generated by an overall reduction in volcanic aerosols during the past century. Because the effects of a single volcano only last a few years, this explanation requires a series of massive eruptions every few years, each one precisely calibrated in its timing and magnitude. We have good records of volcanic eruptions over the last century or two, and good records of the amount of volcanic effluent in the atmosphere over the last few decades, and while they appear to account for some of the bumps and wiggles in the global temperature record shown in Figure 4.1, there is no sign of the sustained pattern of eruptions required to explain the long-term observed warming. As a result, we can safely rule out volcanoes as a source of the observed trend.

4.2.4 Solar variability

Because sunlight is the power source that drives the climate, any change in the amount of sunlight reaching the surface can change the climate. For example, orbital variations and volcanoes affect the climate by modulating the amount of sunlight reaching the surface. There is also variation in the output of the Sun itself: it does not shine with constant brightness, but flickers like an old light bulb (it is 5 billion years old, after all). We do not notice this flickering, however, because it occurs slowly, over periods of months, years, and possibly longer, and because it only changes the Sun's total energy output by a few tenths of a percent. But this variability is large enough to affect the climate. If the Sun's brightness had increased by enough and with the right timing, then this alone could have caused the observed warming of the past century.

Accurate measurements of the Sun's output have been made from satellite instruments since the late 1970s. Over this period, there has been essentially no trend in the Sun's output, only the periodic variation of less than 0.1 percent that occurs over the 11-year solar cycle. Because of the enormous thermal inertia of the oceans, the climate is quite insensitive to such short-term variations. As a result, when put into a GCM, these solar cycle variations produce a very small effect, and are unable to reproduce the observed warming of the last few decades of the twentieth century.

In addition, measurements over the last few decades have shown that, while the surface and lower atmosphere are indeed warming, the stratosphere is *cooling*. This observation is inconsistent with an increase in the Sun's output, which would lead to increases in the temperature of the entire atmosphere. Consequently, the suggestion that increases in solar brightness are the cause of the observed recent warming can be decisively rejected.

But whether changes in the Sun's output could have contributed to earlier warming is a more difficult question. Without direct measurements of the Sun's output from satellites, we must infer solar variability indirectly from measurements of proxies, such as the number of sunspots, which people have been observing and recording for thousands of years. The most recent analyses have concluded that the Sun has brightened by less than 0.1% over the last few hundred years, and this has contributed relatively little to the warming over that time period.

4.2.5 Internal variability

All the potential sources of warming discussed so far involve 'forced variability,' by which we mean that the Earth's climate responds to an imposed change, such as a change in the Earth's orbit, the Sun's brightness, or the arrangement of the continents. But the Earth's climate system is so complex that it can experience variability even with no changes in the factors driving the climate — rather like the wobbling of a spinning top, but much more complex. Such climate variation that is unrelated to any external forcing is called internal variability.

Several prominent patterns of internal climate variability are becoming increasingly well documented and understood. The best known is the Southern Oscillation, a sloshing of warm surface water back and forth across the South Pacific Ocean with a somewhat irregular period of several years. The two phases of the Southern Oscillation, called El Niño and La Niña, each last a year or two. In the El Niño phase, warm surface water builds up at the eastern edge of the tropical Pacific, so the ocean off the west coast of South America warms dramatically. Linked changes in temperature and rainfall extend worldwide, and the Earth's average temperature increases.

This is well demonstrated by the El Niño of 1998, the biggest of the 20th century. Fig. 4.9 shows that the temperature of this year stands head-and-shoulders above surrounding years. This increase in global temperature in turn caused a thermal expansion of the ocean, and an upward surge in average sea level (the inset of Fig. 4.3). The La Niña phase reverses these changes, including a cooling of the Earth's average temperature and a reduction in sea level (also seen Figs. 4.3 and 4.9). Several other characteristic patterns of natural climate variability have now been identified, with periods ranging from a few years to a few decades.

Could such internal variability be responsible for the warming observed over the past century? In other words, could the recent warming be part of a natural oscillation of the climate system?

To begin to answer this question, we look at climate proxy data from before 1800 (Fig. 4.8). Since human activities likely had a minimal impact on the climate before then, that portion of the record gives a good picture of patterns of natural variability in the climate. Between 1000 and 1800, this record shows nothing similar to the rate and magnitude of warming since the late nineteenth century, so if recent warming is due to natural variability, we see no evidence that it has been evident for at least 1000 years.

Going back before 1000 years ago, the proxy climate data are lower in quantity and quality, so we know less about how temperature varied from year to year. Over the past few tens of thousands of years, there is some evidence of rapid climate changes, with average temperature changes of up to a few degrees Celsius occurring over a few decades to a century or so, during transitions into or out of ice-age conditions. These rapid natural climate changes, however, occurred together with rapid reorganization of circulation patterns in the atmosphere and oceans. More work on this is needed, but there is no evidence at present to suggest that such large-scale changes in atmospheric or ocean circulation are occurring in parallel with the observed twentieth-century warming.

We can also gain insight into natural climate variability by using computer simulations of the climate, usually called General Circulation Models or GCMs. (See the Aside below for more information about GCMs). When climate models are run without any human greenhouse-gas emissions, they show variations in global-average temperature from year to year and decade to decade that are very similar to those seen in the climate proxy data before about 1850, but they produce nothing resembling the rapid temperature increases of the past century. We will see below that climate models can generate such rapid warming only when they include human greenhouse-gas emissions.

Finally, the spatial distribution of the observed warming appears inconsistent with internal variability. Any possible mode of internal variability responsible for the recent warming would almost certainly be driven by changes in ocean circulation — just as El Niños are. In those cases, it is warming of the ocean that heats the globe, so we would expect to see greater temperature trends over the ocean than over land. Observations, however, show that the opposite — the land areas of the globe have been warming significantly faster than the oceans.

Considered together, these pieces of evidence suggest that while we cannot definitively exclude natural climate variability as a contributor to recent warming, it is unlikely that natural variability can account for any significant fraction of the recent rapid warming.

Aside: what is a climate model?

Believe it or not, you can get an idea of the job that climate models do (often called General Circulation Models, or GCMs) by thinking about fashion models. It is hard to imagine what clothes will look like on a person if you only see them on a hanger. So fashion designers hire models to wear their clothes at fashion shows, so people can get a better idea of what the clothes will look like when worn.

The fundamental physical laws that govern the behavior of the climate system — conservation of energy, conservation of momentum, and conservation of mass — can be written down in a few equations. But much like clothes on a hanger, it is impossible to look at these equations and get a sense of how the climate will behave. So climate scientists use these equations to construct a simulated Earth — a climate model, or GCM — in the computer. You can test the simulated Earth by comparing its behavior to that of the real Earth. And you can study the simulated Earth in ways that you cannot study the real Earth. You can examine how it responds to various 'what if' scenarios — what if the output of the Sun changed, or what if there were no human emissions of CO_2 — and compare the results to the real climate behavior we have observed, to test various causes proposed for past climate trends. A good example of this will be shown in Section 4.2.6. You can also use a model to predict how the climate will respond to any specified assumption about trends in future emissions of CO_2 and other greenhouse gases.

Unfortunately, the atmosphere is too complex to be represented exactly by any present-day computer, so all climate models make approximations and assumptions to be tractable. The most important simplification concerns the smallest size at which atmospheric processes are represented. Most climate models divide the atmosphere into boxes about 100 kilometers square and one or two kilometers thick vertically, and assume that within each box, all conditions (temperature, humidity, winds, etc.) either are uniform, or can be described by a simple mathematical relationship. Understanding the errors introduced by this approximation, and reducing them by improving the mathematical representations of finer-scale physical processes (called 'parameterizations') is an area of great effort and the source of some of the greatest controversies in climate science.

To check the validity of climate models, scientists examine how well they reproduce a climate period for which we have good data. For example, they might start the model in the year 1500, run it to the present, and examine how well it reproduces the actual climate record. Present models do quite a good job of simulating the global average historical climate record for the world as a whole and for large continental regions. Simulations agree less well with the instrumental record for smaller-scale regions, however, suggesting that we should have less confidence in future climate predictions as we look at smaller scales.

4.2.6 Increases in greenhouse gases

The last potential explanation for the observed warming of the Earth is an increase in greenhouse gas abundances in the atmosphere. As we discussed in Chapter 3, the observed increase since about 1750 can be unambiguously attributed to human activities.

There are several reasons to think that this is the primary explanation for the observed warming. Measurements show the concentration of CO_2 has increased about 30 percent over the last 250 years (Figure 1.1), while other greenhouse gases have increased by similar or larger amounts.

And as we described in Chapter 3, basic physics provides strong theoretical reasons to believe that such an increase in greenhouse gases should warm the Earth. We can see a good example of the greenhouse effect in action on our next-door neighbor, Venus. Venus has a massive and dense atmosphere, with a surface pressure of 90 times that of Earth — equal to the pressure at an ocean depth of 3000 ft — made up almost entirely of CO_2, so Venus' atmosphere has roughly 200,000 times more CO_2 in it than Earth's. With so much CO_2 in the atmosphere, you might expect a massive greenhouse effect, and you would be right. The surface temperature of Venus is hot, around 450°C, hot enough to melt lead. It is hotter even than Mercury, which is located much closer to the Sun.

Further evidence supporting CO_2 as the cause of the recent warming exists in the record of past climate changes. Fig. 4.6 shows a general decrease in temperature over the past fifty million years. The evidence we have suggests that this decrease was associated with a simultaneous decrease in atmospheric greenhouse gases. At the time of peak temperatures, CO_2 abundances were several times higher than today's. CO_2 abundances subsequently decreased, due to an increased rate of chemical weathering and absorption into the ocean due to enhanced biological activity there. As greenhouse gases decreased, the temperature decreased with it. Most evidence suggests these are linked, and it is the decrease in CO_2 and other greenhouse gases that is primarily driving the decrease in temperature, with some contributions from other tectonic processes.

One particular example shows the striking power of greenhouse gases to warm the planet. About 55 million years ago, Fig. 4.6 shows a brief spike in the planet's temperature, an event known as the Paleocene-Eocene thermal maximum or PETM. This warming was rapid (10,000-20,000 years) and intense, with deep-ocean and high-latitude surface waters warming by 4°-8°C. This extraordinary event is thought to have been caused a massive release of greenhouse gases, either methane from marine gas reservoirs on continental slopes or from release of CO_2 from volcanoes.

The association between CO_2 and temperature are even clearer over the last few hundred thousand years. Figure 4.7b shows that CO_2 and temperature are tightly associated with each other as the Earth cycles between ice ages and warm interglacials. This association, however, is more complicated than implied by the correlation. We know that ice ages are initiated by small variations in the earth's orbit. However, these slight orbital changes are small — too small, in fact, to explain the wide temperature swings in Fig. 4.7b by themselves. So something else must be helping the orbital variations produce the observed variations. What most scientists think happens is that the orbital variations cause a slight initial warming, which causes CO_2 and other greenhouse gases to be released by a mechanism that is not presently well understood. One example of the types of mechanisms being considered is that the warming leads to increased biological activity, increasing the rate of decay of organic soils, leading to the release of CO_2. The initial release of greenhouse gases causes more warming, which leads to the further release of greenhouse gases, and more warming. In other words, a positive feedback loop is established. Without the contributions of greenhouse gases, the large amplitude swings of the climate would be impossible[6].

Another reason to suspect greenhouse gases are the main driver of the recent increase in temperatures is that they can explain the recent rise in temperatures — and you cannot explain the warming without it. Figure 4.10 shows such a comparison, between the observed surface temperature record since 1860 and a climate model using three alternative combinations of climate forcing factors. The calculation in panel (a) includes solar variability and volcanoes, but no human effects. This calculation captures some of the bumps and wiggles in the temperature record, suggesting that solar and volcanic effects are indeed affecting the climate. But there are also large differences: in particular, the model does not capture the rapid warming observed since 1970.

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[6] The fact that these ice age-interglacial cycles are initiated by orbital variations explains why the CO_2 changes *lag* the temperature changes. Some skeptics have used this fact to argue that the lag disproves the idea that changing CO_2 affects climate. In fact, the changes in CO_2 are necessary to explain the large temperature changes in Fig. 4.7b, so these data actually provide further evidence that CO_2 and climate are intimately related.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Figure 4.10. Global mean surface temperature anomalies from the surface thermometer record (thin line on all plots), compared with a coupled ocean-atmosphere climate model (thick line). (a) Model includes solar and volcanic effects only. (b) Model includes human greenhouse-gas emissions, aerosols, and ozone depletion, but no solar or volcanic effects. (c) Model includes solar, volcanic, and human effects. Anomalies are measured relative to the 1880-1920 mean. Source: Fig. 12.7, IPCC (2001a).

The model in panel (b) includes the effects of human activities — greenhouse gas emissions, and also sulfur emissions from burning coal and stratospheric ozone depletion, both of which tend to cool the surface — but no solar or volcanic effects. This model captures the rapid warming observed since 1970, as well as the slight global cooling that occurred between 1950 and 1970. The sulfur emissions are particularly important to include because, like volcanic sulfur emissions, they lead to the formation of aerosols, which reflect incoming sunlight and cool the surface. The mid-century period of cooling can be attributed to increased reflection of sunlight from increasing sulfur emissions. Although CO_2 emissions were increasing at this time, the cooling effect from sulfur-based aerosols increasing the reflection of sunlight dominated the warming effect from increased CO_2. Since the 1970s, rapidly increasing CO_2 emissions coupled with slowing growth of sulfur emissions mean that warming from CO_2 now dominates, leading to the rapid warming seen over that period. This model captures this mid-century cooling and rapid, late-century warming, in good agreement with the data. This model run does not, however, capture either the bumps and wiggles in the data or the warming in the early twentieth century, which the previous model run captured better.

The model in panel (c) includes both human emissions and solar and volcanic effects. This model captures all the large-scale features of the historical record: the early twentieth-century warming (mostly due to natural effects), the mid-century cooling (mostly due to sulfur emissions), and the rapid warming of the past few decades (due to greenhouse-gas emissions). This comparison indicates that human greenhouse-gas emissions, volcanic, and solar effects have all contributed to global temperature changes of the past century, but that greenhouse-gas emissions are responsible for the great majority of the rapid, late 20^{th}-century warming.

4.2.7 Summary: are human activities responsible for recent warming?

We have considered six potential causes for the observed recent warming of the Earth. Two of these — orbital variations and tectonic processes — can be decisively eliminated as significant contributors to the 20^{th}-century warming. They are simply too slow to cause rapid warming over a time period of a few decades. Two other processes — volcanic eruptions and changes in solar output — can also be rejected. We have good measurements of solar variations and of volcanic perturbations to our atmosphere over the last few decades and can show that they cannot explain the recent warming. Internal variability is difficult to definitively reject, but there are several reasons why this is an unlikely explanation.

The observed increase in greenhouse gases, on the other hand, turns out to be highly likely for two reasons. First, as we discussed in Chapter 3, there are strong theoretical reason that it would warm the planet. Putting the increase into climate models, we see that the observed increase in greenhouse gases can explain the timing and magnitude of the warming over the last few decades. Second, analysis of our climate going back tens of millions of years reveals that previous climate changes have been at least partially driven by changes in greenhouse gases.

Given the compelling evidence in favor of greenhouse gases and the lack of a legitimate competing hypothesis, greenhouse gases are clearly the most likely explanation for our recent warming. And because humans are responsible for the increase in greenhouse gases, that means that humans are to blame. As a result, the IPCC concludes in its 2007 report that "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

It is important to note how this conclusion is limited. The Earth has been warming for at least 400 years. For the warming before about 1950, however, a significant contribution from non-human factors such as cannot be ruled out. To reflect this, the IPCC's statement specifically avoids positively attributing the pre-1950 warming to humans. Second, the IPCC cannot rule out contributions from a brightening Sun or internal variability to the recent warming, although such a contribution would be small relative to the human-induced warming. That's why the IPCC reports say that humans are responsible for "most" of the warming rather than all of it. Finally, while we know much about the climate system, some aspects of our knowledge remain uncertain. As a result, the IPCC reports says that this conclusion is "very likely," meaning in their carefully nuanced language a 90% chance of being true.

We should also point out that humans can change the climate by mechanisms other than increases in greenhouse gases. For example, cutting down a forest and replacing it with farmland can radically change the local climate. In general, such non-greenhouse gas climate effects tend to cool the climate, thereby offsetting some of the warming from greenhouse gases. While uncertainties in these types of climate impacts are large, our understanding is rapidly improving and we can be reasonably certain that greenhouse gases are the dominant driver of the warming of the last few decades.